1122
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A brief history of sagebrush management in the Great Basin: From removal to reduction and beyond

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On the Ground

- After years of overgrazing in the late 1800s and early 1900s with little to no management, range management efforts shifted to focus on eradication of sagebrush to promote forage production from World War II to the 1970s.
- From the 1970s to present the paradigm shifted to an emphasis on leaving sagebrush intact for the benefit of sagebrush-obligate wildlife.
- However, neither management paradigm has yielded an ideal outcome with approximately 30% of the Great Basin being identified as "poor condition shrubland," with >10% shrub cover and a high ratio of annual to perennial herbaceous cover.
- A combination of new and old restoration methods is needed to restore degraded sagebrush communities to rejuvenate the declining perennial herbaceous understories and increase biotic resiliency of the shrub community.

Keywords: *Artemisia tridentata*, *Bromus tectorum*, Bunchgrass, Cheatgrass, Degradation, Sage-grouse, Tebuthiuron, Wyoming big sagebrush.

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Introduction

Few plant species are as iconic to the Intermountain West of North America as big sagebrush (*Artemisia tridentata* Nutt.). The shrub served a multitude of medicinal purposes for various Native American tribes and has been recognized as the official state flower of Nevada since 1917.[1,2] Sagebrush plants also provide ecosystem benefits such as creating resource or fertile islands, defined as the accumulation of nutrients from leaf litter and aeolian deposition beneath the shrub canopies, which provide nutrients to understory bunchgrasses and forbs.[3] In addition, they provide habitat for species like greater sage-grouse (*Centrocercus urophasianus*) and comprise up to 99% of the grouse's diet in winter.[4]

Yet, despite its status as an iconic and foundational species throughout much of the West, big sagebrush has at times been considered a nuisance (pre-1960s),[5,6] and since the 1960s sagebrush it has been viewed more favorably as habitat for sagebrush obligate wildlife[7] and a line of defense against invasive species.[8-10] From the early homesteading and ranching days of the 1800s through the early 1900s, overgrazing in the Great Basin led to a decline in native bunchgrasses and forbs, and, some contend, an overabundance of big sagebrush.[11,12] Others have maintained that thick shrub cover has been prevalent in the region since before European arrival.[13] Nevertheless, in the ensuing years, from the 1940s through the 1960s, removing sagebrush to increase perennial bunchgrass production became a priority of range management efforts in the sagebrush steppe.[5,6,14,15] Since then, the paradigm of sagebrush management has shifted from one of complete removal to a "hands-off" approach of leaving dense sagebrush with depleted herbaceous understories undisturbed, often for the benefit of wildlife.[7,16-18]

However, none of these management paradigms has yielded an ideal outcome. Dense Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. *Wyomingensis*, Beetle & Young) stands with depleted perennial herbaceous understories are at risk of higher-severity wildfires.[19,20] A site with dense sagebrush and few bunchgrasses lacks biotic resistance and has diminished ability to recover from wildfire or other disturbances.[21,22] On the other hand, complete removal of big sagebrush from a site with a depleted perennial herbaceous understory may compromise any resistance the sagebrush may have provided against invasive annual grasses.[10,21] Invasive annual grasses like cheatgrass (*Bromus tectorum* L.) increase fine fuel loads, resulting in a positive feedback loop and leading to a cycle of more frequent wildfires and the reestablishment of annual grasses.[8-10]

As efforts to manage sagebrush in the western United States have changed, the sagebrush ecosystem remains one of the most imperiled in the country; it now occupies about half of its historic range.[23] It is estimated there are millions of hectares of degraded sagebrush rangeland with high canopy cover and depleted herbaceous understories.[24,25] When degraded sagebrush rangelands are affected by fire—and they inevitably will be—they are at risk of invasion by exotic annual grasses. Additionally, much of the sagebrush ecosystem is at risk of invasion by exotic annual grasses, including both cheatgrass and medusahead (*Taeniatherum caput-medusae* (L.) Nevski).[23,26,27] This suggests that past management efforts to restore degraded sagebrush communities appear to have been unsuccessful in maintaining a resilient and resistant sagebrush ecosystem, which begs the question, how should the sagebrush ecosystem be managed? How can land managers best attain a desired Wyoming big sagebrush canopy cover that allows for increased perennial herbaceous abundance, provides habitat and forage for wildlife, and remains resilient to disturbance and resistant to invasive species as climatic conditions continue to change at the landscape scale? Answering these questions requires an understanding of how sagebrush management arrived at its current paradigm, and the role different abiotic and biotic characteristics have played in determining management outcomes. In this paper, we explore the evolution of sagebrush management, address the implications of different management paradigms, and contemplate the potential for further refinement of management efforts through use of precision decision-support and management tools. First, we discuss the period in the mid-1900s when land managers prioritized sagebrush removal for the sole benefit of perennial forage production. Next, we discuss how, in the 1970s onward, the focus shifted toward maintaining sagebrush for the purpose of wildlife habitat. Finally, we address the need for a new paradigm—one that focuses on facilitating resilient landscapes that realize multiple benefits.

Early days: prioritizing perennial forage

By the time the Taylor Grazing Act was passed in 1934, rangelands of the Intermountain West had been transformed by a pattern of overuse and conversion to cultivated crop production.[28] The preceding era was characterized by rampant overgrazing, largely a consequence of the open range policy, which allowed livestock owners to freely graze vast tracts of public land throughout the West.[28,29] This incentivized ranchers to use as much of the grazing resource (the "commons") as possible to maximize production, often at the expense of others—a trend referred to as the "tragedy of the commons."[28,30] The Taylor Grazing Act established grazing districts and grazing allotments on public lands, created the agency that would become the Bureau of Land Management, and ultimately laid the groundwork for improved management of public rangelands.[31] The era of uncontrolled grazing on the range was over. In its wake, the saga of overgrazing native bunchgrasses is believed to have left an excess of sagebrush in some large areas of the Intermountain West.[12,29] However, historical accounts on sagebrush abundance before European settlement are inconsistent, making it somewhat difficult to gauge the validity of this claim.[11-13]

Whatever the case, in the years following the Second World War, conventional management wisdom posited that sagebrush should be completely removed—often through mechanical control (chaining, railing, grubbing, or rotobeating) or herbicide applications (2,4-D [{2,4-dichlorophenoxy} acetic acid] or 2,4,5-T [2,4,5-trichlorophenoxyacetic acid])—with the primary goal of improving perennial bunchgrass growth to increase grazing capacity.[5,6,32] Certain mechanical methods like rotobeating, which use rotating drums attached to flails that "beat up" and shred shrubs, were effective for killing mature, tall sagebrush, but less successful when it came to controlling short or young sagebrush.[14,32] Other mechanical methods, such as plowing or disking, were successful in killing sagebrush plants of all age classes, but in the process killed much of the desired forage species in the understory.[32] Through aerial spraying of 2,4-D or 2,4-5-T, especially at high rates and using diesel oil as a carrier, a land manager could expect high sagebrush mortality, while bunchgrasses in the understory were left intact.[5,32] In areas of the northern Great Basin with healthy understories of perennial bunchgrasses, aerial spraying became the most popular method for sagebrush removal.[15]

It was said that eradicating sagebrush could pay for itself many times over, increasing grazing capacity up to 25-fold.[32] In Wyoming, researchers found that native bunchgrass production increased two to three times on rangelands with a healthy herbaceous understory 1 year after controlling sagebrush with 2,4-D.[5] However, it is important to note that crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.) was often seeded in combination with treatments aimed at sagebrush eradication. Crested wheatgrass is an introduced species that originated in the steppes of Siberia, and is well-adapted to the climate of the sagebrush rangelands of the Intermountain West.[33,34] Crested wheatgrass was seeded to occupy areas previously dominated by sagebrush, especially where a healthy understory of native bunchgrasses was absent.[32] Although this carried an additional expense, crested wheatgrass was more grazing tolerant and could be grazed earlier in the season than native grasses.[32,34] So, when combined with sagebrush removal, it often brought greater returns in grazing capacity.[32]

During the mid-1900s, millions of hectares in the West received some kind of sagebrush control treatment.[15,32] By 1974, over 1.8 million hectares (around 4.5 million acres) of federally administered public land had been treated for sagebrush control in Idaho, Montana, Nevada, Oregon, Utah, and Wyoming.[15]

However, problems arose with big sagebrush removal. Cheatgrass, an exotic annual grass, had arrived in many western states by the end of the 1800s, and quickly began occupying disturbed sites where native sagebrush and bunchgrass cover had been depleted.[35] Researchers[14] soon found that sagebrush removal in the absence of a healthy perennial bunchgrass community led to exotic annual grass invasion; on poor-condition southeast Oregon rangelands with dense big sagebrush and depleted herbaceous understories, Hedrick et al.[14] observed an increase from virtually no cheatgrass to 224 kg/ha and 370 kg/ha (200 lb/ac to 330 lb/ac) as a result of killing big sagebrush with rotobeating and 2,4-D, respectively.

Cheatgrass can exclude perennial grasses due to earlier germination, faster root penetration and growth, and faster seed set.[36,37] This is even more problematic on warm, dry Wyoming big sagebrush rangelands with sparse perennial bunchgrass cover to compete with exotic species, as was often the case where overgrazing had occurred.[21,22,29] Combine this competitiveness with the increased flammability that comes with earlier senescence and a more continuous fuel bed, and you have a recipe for a positive feedback loop, where cheatgrass invasion leads to a cycle of more frequent wildfires, reestablishing itself year after year.[8-10,38]

Exotic annual grass invasion was not the only repercussion of shrub eradication. Land managers and researchers also became aware of the effects of sagebrush removal on wildlife, in particular, greater sage-grouse (*Centrocercus urophasianus*, Bonaparte).[16,17] Sage-grouse rely on sagebrush for both their diet and nesting habitat.[39,40] It is not surprising then, that in the 1960s and 1970s, researchers observed fewer sage-grouse nesting sites and reduced populations where big sagebrush was removed through 2,4-D.[16,17]

A time of transition: shifting priorities

The 1960s and 1970s ushered in a new era for sagebrush management in the West. It was a time marked by heightened public awareness of humankind's environmental footprint,[41] dwindling public acceptance of pesticide use,[42] and new environmental legislation.[28,43] Mounting public concern regarding wildlife and air and water quality captured the attention of US senators and representatives, eventually giving rise to new legislation requiring additional accountability and public input on projects and practices affecting federally administered land.[28,43] The most salient among these include the National Environmental Policy Act (NEPA) of 1969, the Endangered Species Act (ESA) of 1973, and the Federal Land Policy and Management Act (FLPMA) of 1976.[28] NEPA required agencies like the Bureau of Land Management (BLM) to draft environmental impact statements for actions affecting public lands.[28,43] In addition, FLPMA required agencies to draw up land use plans, which took the form of resource management plans prepared in tandem with environmental impact statements.[44] NEPA and FLPMA both provided an avenue for public engagement, allowing citizens to comment on proposed actions affecting public lands as part of the environmental impact statements and resource management plans processes.[28,43,44] Ultimately, NEPA and FLPMA required land management agencies to commit more time and resources toward administrative processes, leaving less time to devote to implementing restoration projects.[28,45,46] ESA, on the other hand, provided protection against any action that would alter the habitat of or directly harm a listed species.[28,47]

These changes set the stage for subsequent declines in sagebrush treatments on public rangelands from the 1970s onward. Treatment information is relatively inconsistent; however, the Land Treatment Digital Library, which compiles data on treatments on public land, includes at least 1,000 treatment entries (i.e., herbicide/weed control, prescribed burn, and vegetation manipulation) West-wide, involving some kind of brush management in the 1960s.[48] In the following decade, as NEPA and FLPMA went into effect, that number plummeted to less than 300.[49] Sagebrush removal treatments did not quite screech to a halt, but land managers had pumped the brakes.[48,50]

After the start of the new millennium, sagebrush treatments in the Great Basin remained relatively static, as land managers concentrated efforts on maintaining adequate nesting, brood-rearing, and winter habitat for greater sage-grouse.[7,50] This came to a head in 2010 when, after a series of petitions to list the greater sage-grouse, the US Fish and Wildlife Service determined that sage-grouse required protection under ESA due to continuing population declines and habitat fragmentation, but the listing was precluded due to listing other, higher-priority species.[49-51] Over the next 5 years, state and federal agencies, private landowners, and nongovernmental organizations took major steps toward conserving sage-grouse habitat, and in 2015, the USFWS concluded that protection under ESA was not warranted.[48,50] Regardless, the threat of an ESA listing had effectively stymied sagebrush treatments in the 2000s and 2010s.[50]

Currently, over 16.5 million hectares (40.7 million acres) or roughly 30% of the Great Basin is characterized as "poor condition shrubland" (Fig. 1; Table 1). Poor condition sagebrush rangeland has been defined as sites with shrub cover >10% and a high annual-to-perennial grass and forb cover ratio.[25] Sites with <10% shrub cover were delineated as an annual grassland and not a degraded shrubland.[25] This is a problem for several reasons. First, and perhaps most obvious, biological competition from dense sagebrush stands inhibits establishment and growth of both native and introduced perennial bunchgrasses.[24,52] In addition, areas with high canopy cover of sagebrush can increase wildfire severity, creating a negative outcome for warm, dry Wyoming big sagebrush sites with bunchgrasses predominantly located directly beneath shrub canopies.[19,20,53,54] This magnifies the potential for bunchgrass mortality and reduces the chances of bunchgrasses repopulating the area after a fire.[21,53-55] Without perennial bunchgrasses to serve as a line of defense, resistance to invasion by exotic annual grasses is severely compromised.[21,22]

The lack of a perennial understory in a sagebrush community can have a cascading effect on sage-grouse habitat. Degraded sagebrush rangelands are at an elevated risk of exotic annual grasses replacing shrubs and native herbaceous

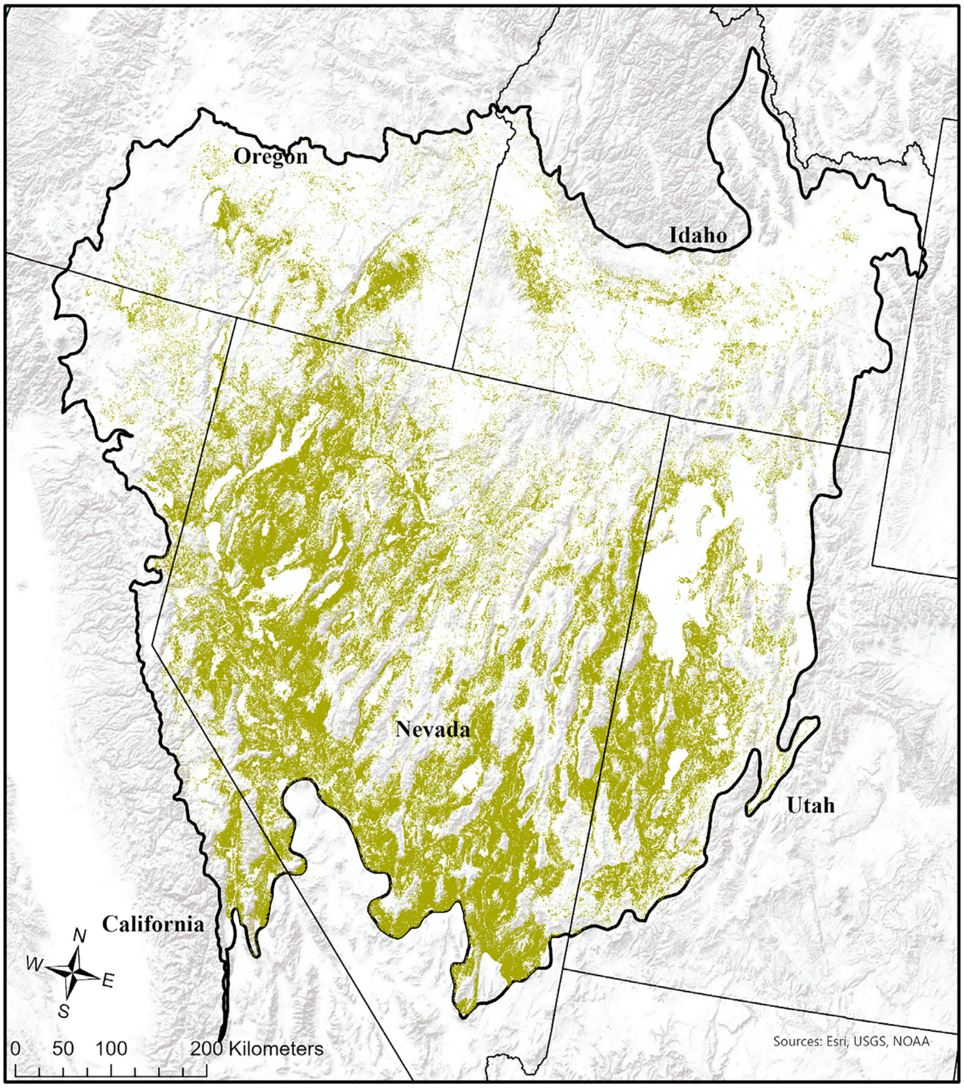

Figure 1. The area of degraded sagebrush (in yellow) in the Great Basin. This area was characterized by the SageCon Landscape Planning Tool as "poor condition shrubland," defined as greater than or equal to 10% shrub cover and a high annual-to-perennial grass and forb cover ratio.[54] Over 16.5 million hectares, or roughly 30% of the total area of the Great Basin falls within this category. See Table 1 for a breakdown of all sagebrush rangeland conditions in the Great Basin as defined by the SageCon Landscape Planning Tool.

species after fire.[10,21,56] With no shrubs or native perennial bunchgrasses for cover and no forbs for food, it is no wonder that sage-grouse tend to avoid exotic annual grass-dominated sites.[57-60] Exotic annual grass invasion is considered one of the top threats to the sagebrush ecosystem and sage-grouse.[21,22,61,62]

Recent numbers indicate more than a half million hectares (1.24 million acres) of sagebrush rangeland have transitioned to poor condition every year over the last 20 years, largely a result of ecosystem dysfunction associated with exotic annual grasses.[62] Smith et al.[63] determined the Great Basin experienced an eight-fold increase in the total area dominated by exotic annual grass from 1990 to 2020.

With this threat in mind, it appears that neither complete eradication nor maintaining degraded Wyoming big sagebrush stands has worked in the best interest of the ecosystem.[23,24,64] Management efforts over the last 100 years have demonstrated that neither approach should be used to manage sagebrush rangelands, and both have incited the proliferation of invasive exotic annual grasses. Alternatively, we propose that a new management paradigm is imperative—one that bolsters biotic resistance to invasion and resilience to disturbance by promoting the growth of native perennial bunchgrasses interspersed among a healthy overstory of big sagebrush.[21,22,65-68]

Current treatments and beyond: selective thinning

So far, we have addressed two opposite ends of the sagebrush management spectrum: complete eradication and leaving degraded sagebrush untouched. For better or worse, in the last 50 years, a greater emphasis on maintaining wildlife habi-

Table 1
Great Basin conditions: The area (measured in hectares and percent of total area) occupied by each threat-based sagebrush ecostate model within the Great Basin as defined by the SageCon Landscape Planning Tool rule set.[54]

Ecostate	Hectares	Land area (%)	Rule set
A: Good condition shrubland	8,110,725.39	14.73%	Tree cover <5% and Shrub cover ≥10% and AFG:PFG ratio <0.333
A-C: Intermediate condition shrubland	11,448,698.13	20.80%	Tree cover <5% and Shrub cover ≥10% and AFG:PFG ratio 0.333-1.0
B: Good condition grassland	1,650,942.54	3.00%	Tree cover <5% and Shrub cover <10% and AFG:PFG ratio <0.333
B-D: Intermediate condition grassland	2,472,933.87	4.49%	Tree cover <5% and Shrub cover <10% and AFG:PFG ratio = 0.333-1.0
C: Poor condition shrubland	16,581,710.43	30.12%	Tree < 5% and Shrub cover ≥10% and AFG:PFG ratio ≥1.0
D: Poor condition grassland	6,827,597.37	12.40%	Tree cover <5% and Shrub cover <10% and AFG:PFG ratio ≥1.0
Juniper and tree: low-mid cover	5,850,425.34	10.63%	Tree cover = 5-20%
Juniper and tree: high cover	2,111,875.11	3.84%	Tree cover ≥21%
Total	55,054,908.18	100.00%	

AFG indicates annual forb and grass; PFG, perennial forb and grass.

tat has resulted in the latter, with a dramatic decline in active sagebrush management.[25,48,50] Although the intentions of this "hands-off" approach are noble, the outcomes of past sagebrush management paradigms have resulted in a patchwork of large, mature, often degraded sagebrush stands that are now more vulnerable to further degradation and invasion by exotic annual grasses—a trend that is accentuated by an increasing footprint of wildfire.[24,25,27,29,67] However, complete eradication of sagebrush, especially without successfully reestablishing native perennial bunchgrasses and forbs, also paves the way for invasion by exotic annuals.[8,14,69] In short, both hands-off and eradication approaches to sagebrush management can serve as different pathways to the same destination.[8-10]

This draws us back to that ever-pertinent question, what might sagebrush management entail in the future? How can land managers ameliorate this growing problem of degraded sagebrush stands, which inevitably burn and are subsequently overtaken by annual grasses?[8,10,22,70] How can land managers simultaneously sustain a heterogeneous sagebrush landscape that serves multiple ecosystem goals and augments biotic resistance and resilience?[21,22]

Although the discussion so far has been largely black-and-white, the answer may lie in a gray area in between. This "gray area" involves selectively thinning or reducing high canopy cover of sagebrush in an effort to enhance biotic components like native perennial bunchgrass and forb density and ultimately foster a mix of sagebrush and perennial herbaceous species.[21,22,24] Depending on the situation, this might mean leaving a desired Wyoming big sagebrush canopy cover of around 10% to 12%, which is close to the natural range of variation for Wyoming big sagebrush in this environment.[24,71]

An assortment of tools have been employed to thin sagebrush in the past, ranging from herbicide to mowing to rotobeating to prescribed burning.[6,32] Prescribed fire had been considered an appropriate option to reducing shrub cover and increasing perennial herbaceous biomass production, but is no longer a viable approach because of the threat of invasive annual grasses, the time frame for sagebrush recovery, and the loss of sage-grouse habitat.[72,73] Mowing, on the other hand, usually kills most mature sagebrush plants.[69,74] It has also been shown to reduce canopy cover in Wyoming big sagebrush for up to 20 years,[74] and mowing with both intact and depleted perennial herbaceous understories can increase exotic annual grasses.[69,75,76] Rotobeating has been demonstrated to be effective at reducing tall, mature big sagebrush stands, without damaging herbaceous vegetation or small sagebrush plants.[6] However, it is limited to terrain that is relatively rock-free.[6,32] These traditional methods and tools all produce physical disturbance to the system, leaving the treated sites vulnerable to annual grass invasion.

The last 50 years have also seen the advent of a new tool that allows for selectively thinning sagebrush while preserving bunchgrasses and forbs in the understory. In the 1970s, researchers began experimenting with tebuthiuron (*N*-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-*N*,*N*′-dimethylurea), a photosystem II inhibiting herbicide that is soil-applied in a pelletized form and absorbed through plant roots.[77,78] In these initial years, higher rates were often used, similar to those used in earlier work with 2,4-D.[79,80] These higher rates (≥1 kg ai/ha [0.89 lb/ac]) could achieve sagebrush control on par with 2,4-D, but at the cost of herbaceous yield, including both grasses and forbs.[80] However, later studies established that when applied at lower rates (<1 kg ai/ha [0.89 lb/ac]), only plants within a 0.5-m (1.64 feet) radius of the pellet are affected, creating a thinning effect.[77] These reduced rates cause defoliation to occur over the course of 1 to 3 years, leaving "skeletons" of sagebrush plants still standing.[81,82] This thinning effect may also have benefits for maintaining adequate cover for wildlife.[81-83] Moreover, with the help of modern technology like high precision GPS devices, satellite-based mapping of sagebrush canopy cover, and unmanned aerial systems, it may be possible to use herbicides like tebuthiuron as a precision tool to this end. Unmanned aerial systems are already being enlisted to ignite prescribed fires on grasslands[84] and for crop protection applications,[85] and they could be used to precisely apply low rates of tebuthiuron where needed to selectively thin dense big sagebrush stands to an ideal canopy cover.[24] Herbicide treatments also avoid soil disturbance, thereby reducing the risk of invasion by annual grass.[86]

On an important note, steps must be taken to avoid the mistakes of past management paradigms. A healthy understory is vital, and treatments that involve thinning or reducing sagebrush with degraded herbaceous understories should be complemented with treatments to seed deep-rooted perennial bunchgrasses to rejuvenate these understories.[22,66,87,88] With a higher density of fire-tolerant bunchgrasses like bluebunch wheatgrass (*Pseudoroegneria spicata*, Pursh) and bottlebrush squirreltail (*Elymus elymoides* [Rafinesque] Swezey), a Wyoming big sagebrush community is better-equipped to recover and is more resilient in the wake of wildfire.[22,55,66] With bunchgrasses occupying the interspaces between shrubs and using nutrients and water, those resources become unavailable to exotic annuals, and the community has a more robust barrier against would-be invaders.[22,66] In order to successfully establish bunchgrasses and forbs, however, dense, high canopy cover stands of Wyoming big sagebrush may need to be thinned or reduced to prevent competition with seeded species.[24,81] Drill seeding is often more successful than broadcast seeding, and this often requires sagebrush to be thinned or reduced.[32,86,88] Some have found success with interseeding into standing sagebrush,[89] although this appears to be dependent on shade conditions and proximity to sagebrush plants, and would also be highly dependent on moisture availability in a given year.[89]

Depending on the year, repeated seeding treatments may be necessary, as seeding efforts in harsh Wyoming big sagebrush environments have been met with variable success.[22,75,87,90] Meanwhile, applications of additional herbicides, like imazapic, may be needed should exotic annual grasses pose a significant threat.[91] As such, promoting resilience and resistance will require a long-term adaptive management strategy that includes repeated vegetation monitoring.[92] As part of this adaptive management approach, land managers will need to plan ahead, but remain vigilant, dynamic, and ready to alter this strategy based on monitoring throughout the growing season.[92] Additionally, land managers need to be able to protect their restoration investments from wildfires and further disturbances, which can quickly undo the progress made.[93]

With that said, further research is critical to understanding the effectiveness of various thinning and seeding methods in high canopy cover Wyoming big sagebrush communities. Multiple studies have demonstrated successful thinning in mountain big sagebrush sites,[81,82,94] where higher precipitation and cooler temperatures provide an environment conducive to herbaceous growth post treatment.[21] The challenge moving forward will be doing the same for Wyoming big sagebrush environments, where warm, dry conditions prevail, and where resilience and resistance are inherently lower.[21] Overcoming this hurdle will involve ascertaining appropriate sagebrush reduction and seeding methods, as well as, selection for or development of herbaceous species to optimize the potential for successful restoration at a given site. Equipped with this information and an adaptive management strategy, land managers will be better prepared to make decisions that foster a heterogeneous sagebrush-bunchgrass community—one that realizes multiple ecosystem benefits, has a reinforced ability to recover in the aftermath of disturbance, and is steadfast in the face of invasion.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. The authors certify they have no financial interest in the subject matter discussed in the manuscript.

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